



Status and prospects of nPDF global analyses

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Nuclear modifications of parton distributions

Nuclear PDFs (nPDFs) often described in terms of

$$\underset{\text{bound-proton PDF}}{f_i^{p/A}}(x, Q^2) = \underset{\text{nuclear modification}}{R_i^{p/A}}(x, Q^2) \underset{\text{free-proton PDF}}{f_i^p}(x, Q^2)$$

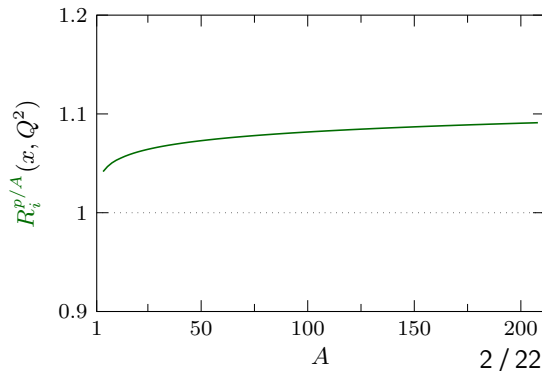
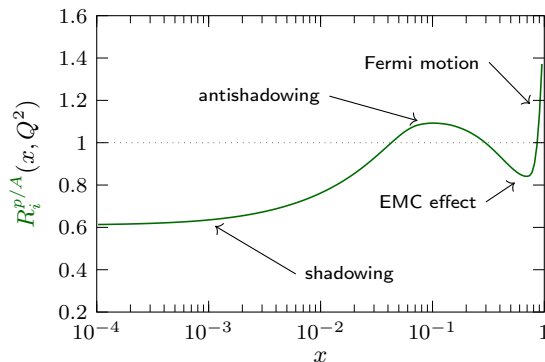
PDFs of the full nucleus are then constructed with

$$f_i^A(x, Q^2) = Z \underset{\text{bound-proton PDF}}{f_i^{p/A}}(x, Q^2) + (A - Z) \underset{\text{bound-neutron PDF}}{f_i^{n/A}}(x, Q^2)$$

and assuming $f_i^{p/A} \xleftrightarrow{\text{isospin}} f_j^{n/A}$

The nuclear effects grow as a power-law in the nuclear mass A

- Not enough data to fit each nucleus independently
- Need a global analysis across different masses!

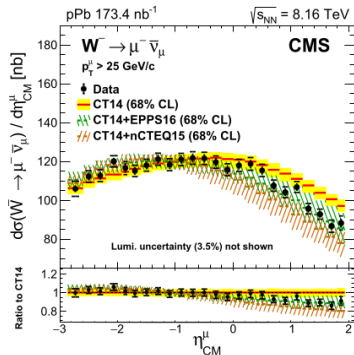
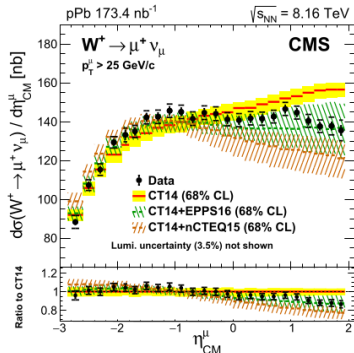


Latest and next generation NLO nPDF global fits

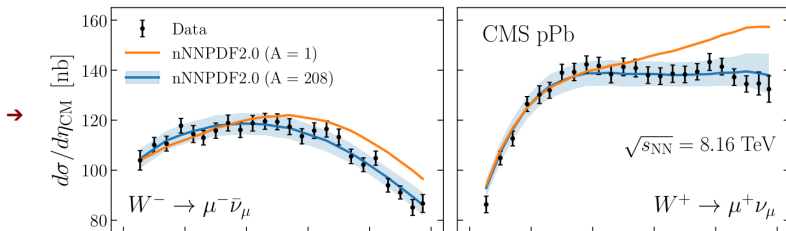
	EPPS16	nNNPDF2.0	nCTEQ15WZSIH	nCTEQ15HIX	EPPS21 <i>prelim.</i>
IA NC DIS	✓	✓	✓	✓	✓
+ JLab NC DIS				✓	✓ <i>new!</i>
ν A CC DIS	✓	✓			✓
pA DY	✓		✓	✓	✓
π A DY	✓				✓
RHIC dAu π^0, π^\pm	✓		✓		✓
LHC pPb π^0, π^\pm, K^\pm			✓		
LHC pPb dijet R_{FB}	✓				
→ dijet R_{pPb}					✓ <i>new!</i>
LHC pPb D^0					✓ <i>new!</i>
LHC pPb W,Z Run 1	✓	✓	✓		✓
+ Run 2 pPb W		✓	✓		✓ <i>new!</i>
Q, W cut in DIS	1.3, N/A GeV	1.87, 3.5 GeV	2.0, 3.5 GeV	1.3, 1.7 GeV	1.3, 1.8 GeV
Data points	1811	1467	828	1564	2023 <i>prelim.</i>
Free parameters	20	256	19	19	24 <i>prelim.</i>
Error analysis	Hessian	Monte Carlo	Hessian	Hessian	Hessian
Error tolerance $\Delta\chi^2$	52	N/A	35	35	35 <i>prelim.</i>
Free-proton PDFs	CT14	NNPDF3.1	~CTEQ6M	~CTEQ6M	CT18A <i>prelim.</i>
HQ treatment	S-ACOT	FONLL	S-ACOT	S-ACOT	S-ACOT
Indep. flavours	6	6	5	4	6
Reference	EPJC 77, 163	JHEP 09, 183	PRD 104, 094005	PRD 103, 114015	TBA

W bosons in pPb at 8.16 TeV

[CMS, Phys.Lett.B 800 (2020) 135048]



[Abdul Khalek, Ethier, Rojo & van Weelden, JHEP 09 (2020) 183]



Potential probes of the flavour separation (and strangeness):

- $u\bar{d} (u\bar{s}, c\bar{s}) \rightarrow W^+$
- $d\bar{u} (s\bar{u}, s\bar{c}) \rightarrow W^-$

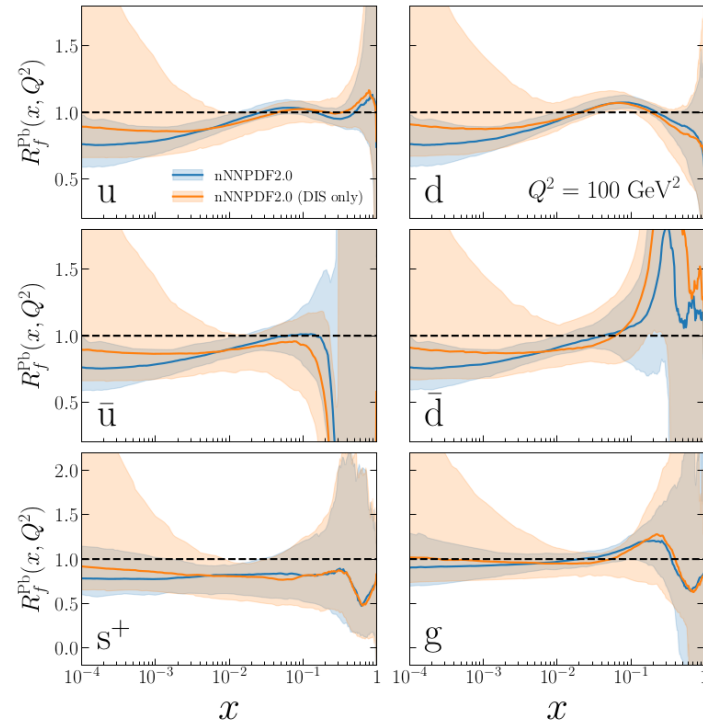
Remember: small- x , high- Q^2 quarks and gluons correlated by DGLAP evolution \rightarrow constraints for gluons

Increased statistics for W bosons in the 8.16 TeV data set

\rightarrow Included in nNNPDF2.0 and nCTEQ15WZ

W/Z bosons in pPb at 5.02 TeV and 8.16 TeV – impact in nNNPDF2.0

[Abdul Khalek, Ethier, Rojo & van Weelden, JHEP 09 (2020) 183]



Flexible neural-network parametrization
(256 free parameters)

Includes CMS and ATLAS W/Z data

Compared to DIS-only fit:

- Preference for EMC effect both in u and \bar{d}
- Clear evidence for small- x shadowing

nNNPDF2.0 does not use fixed-target DY data

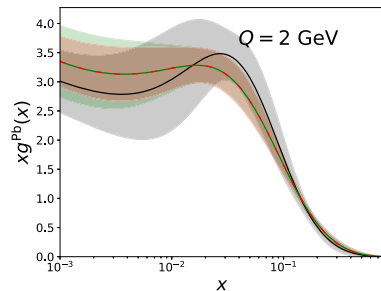
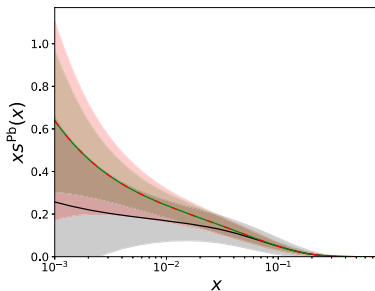
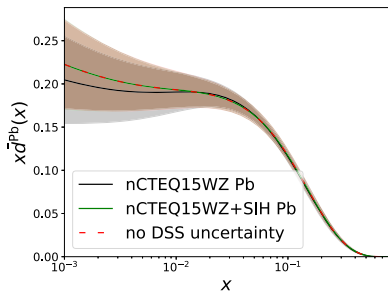
→ W/Z data have to compensate

Here:

$$R_f^A(x, Q^2) = \frac{Z f_f^{p/A}(x, Q^2) + (A-Z) f_f^{n/A}(x, Q^2)}{Z f_f^p(x, Q^2) + (A-Z) f_f^n(x, Q^2)}$$

W/Z bosons and inclusive hadrons – impact in nCTEQ15WZSIH

[Duwentäster *et al.*, Phys.Rev.D 104 (2021) 094005]



nCTEQ15WZ [Kusina *et al.*, Eur.Phys.J.C 80 (2020) 968]

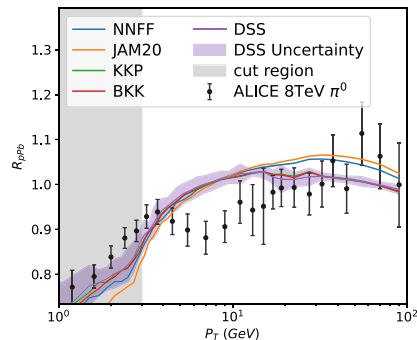
includes also ALICE & LHCb W/Z data

➔ Most extensive EW-boson data set to date

Further gluon constraints in nCTEQ15WZSIH from inclusive hadron production

■ One needs to keep an eye on fragmentation function uncertainties

▶ Partially cancel in the R_{pA}



Need to mitigate free-proton PDF uncertainty

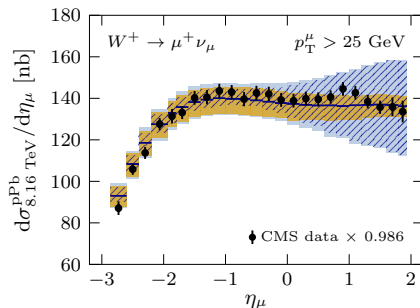
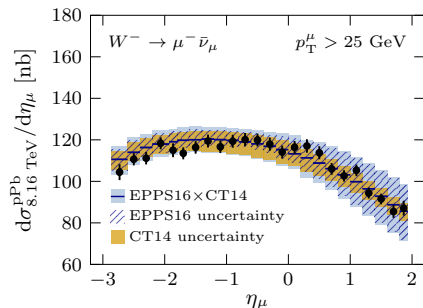
Absolute cross sections carry large proton-PDF uncertainty!

Should not be neglected when fitting the nPDFs!

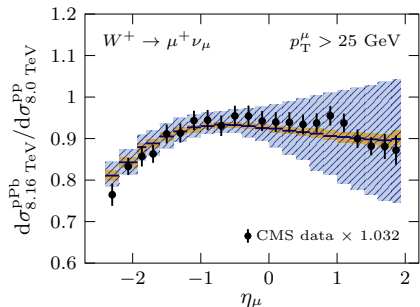
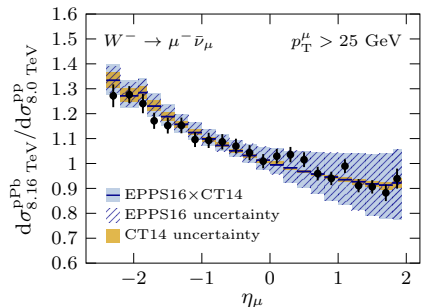
Wherever possible, we use nuclear modification ratios to cancel the free-proton PDF uncertainty

For Ws at 8.16 TeV, we formulate a mixed-energy nuclear modification ratio

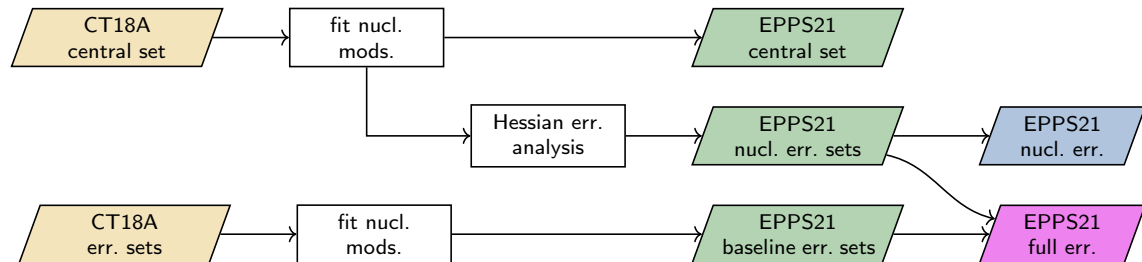
$$R_{\text{pPb}} = \frac{d\sigma_{8.16 \text{ TeV}}^{\text{pPb}}/d\eta_\mu}{d\sigma_{8.0 \text{ TeV}}^{\text{pp}}/d\eta_\mu}$$



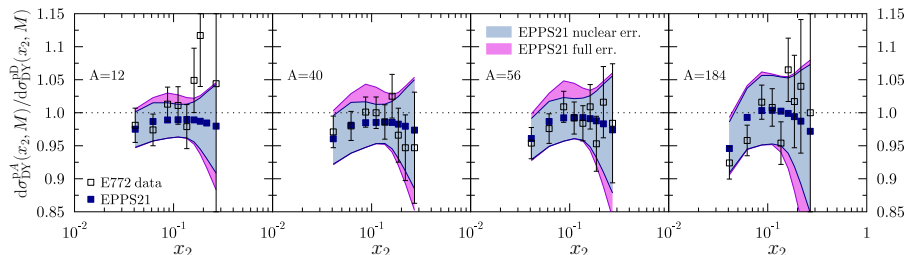
↓ Cancel proton-PDF uncertainty ↓



We study baseline-PDF sensitivity by fitting nuclear modifications separately for each CT18A error set



Baseline error mostly subdominant in the observables we fit, but shows up e.g. in the fixed-target DY

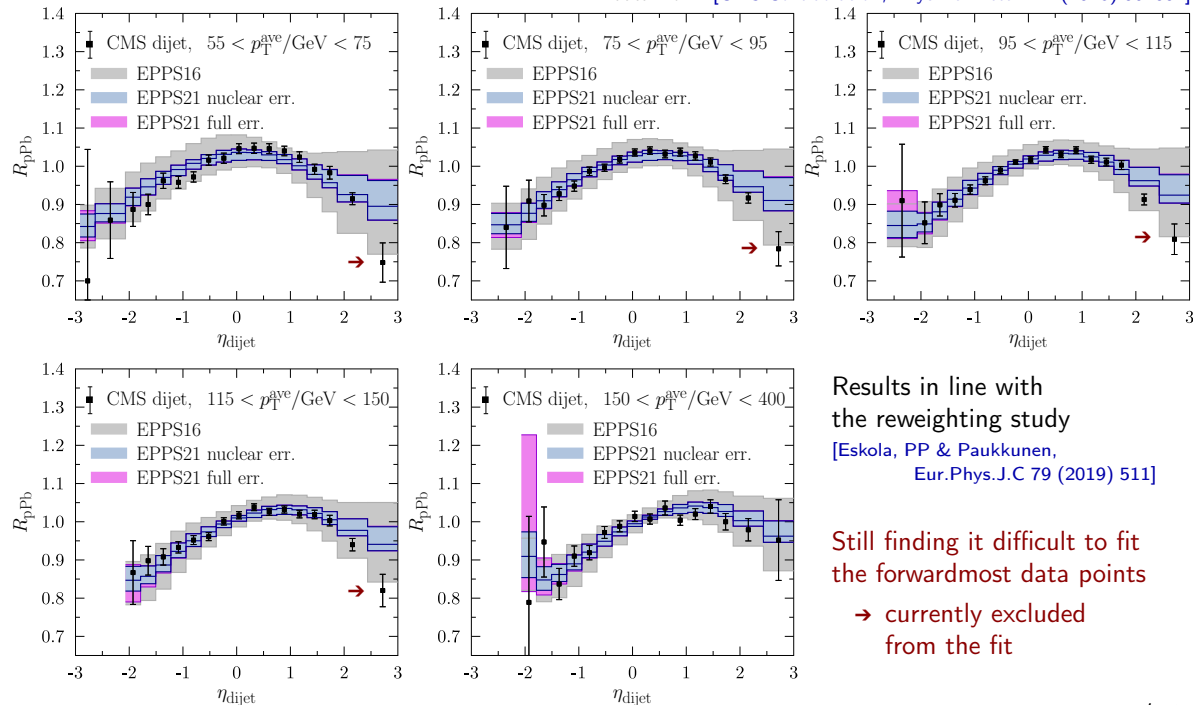


Dijets at 5.02 TeV *new!*

preliminary results,

Ref: [Eskola, PP, Paukkunen & Salgado, arXiv:2106.13661]

data from: [CMS Collaboration, Phys.Rev.Lett. 121 (2018) 062002]



Results in line with
the reweighting study

[Eskola, PP & Paukkunen,
Eur.Phys.J.C 79 (2019) 511]

Still finding it difficult to fit
the forwardmost data points

→ currently excluded
from the fit

D^0 s at 5.02 TeV – backward *new!*

Ref: [Eskola, PP, Paukkunen & Salgado, arXiv:2106.13661] *preliminary results,*

Excellent fit!

Results in line with
the reweighting study

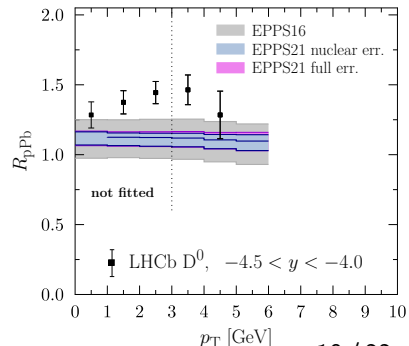
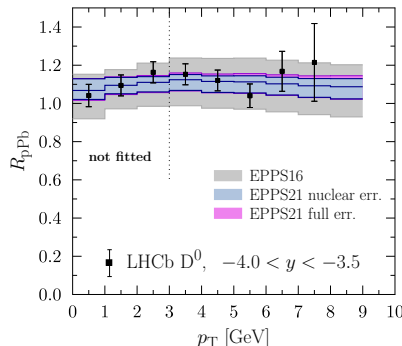
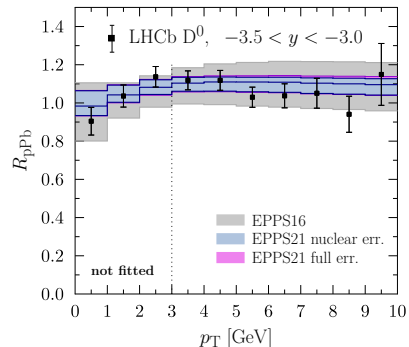
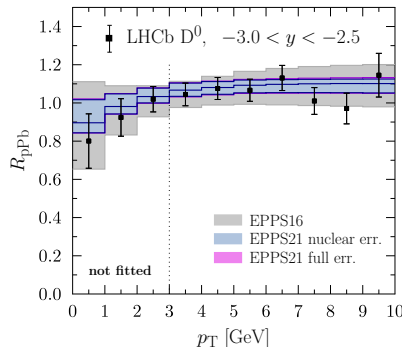
[Eskola, Helenius, PP & Paukkunen,
JHEP 05 (2020) 037]

Using the NLO pQCD
S-ACOT- m_T GM-VFNS

[Helenius & Paukkunen,
JHEP 05 (2018) 196]

Using a $p_T > 3$ GeV cut
to reduce theoretical
uncertainties

data from: [LHCb Collaboration, JHEP 10 (2017) 090]



D^0 s at 5.02 TeV – forward *new!*

Ref: [Eskola, PP, Paukkunen & Salgado, arXiv:2106.13661] *preliminary results,*

Excellent fit!

Results in line with
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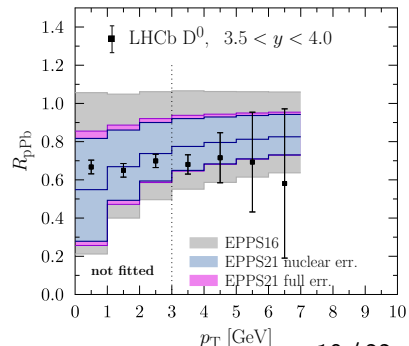
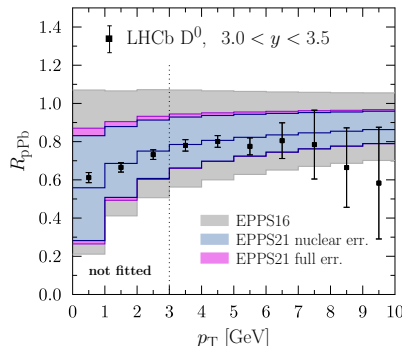
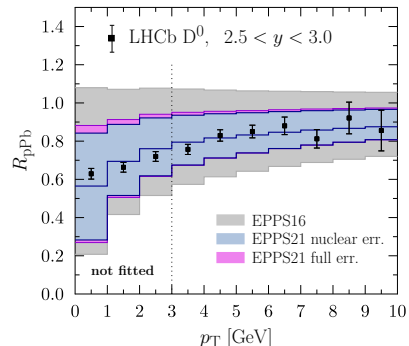
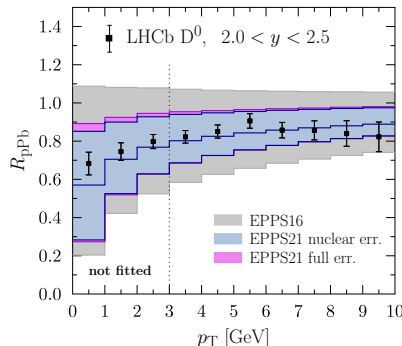
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Excellent fit!

Using the mixed-energy nuclear modification ratio

$$R_{\text{pPb}} = \frac{d\sigma_{8.16 \text{ TeV}}^{\text{pPb}}/d\eta_\mu}{d\sigma_{8.0 \text{ TeV}}^{\text{pp}}/d\eta_\mu}$$

to cancel the free-proton PDF uncertainty

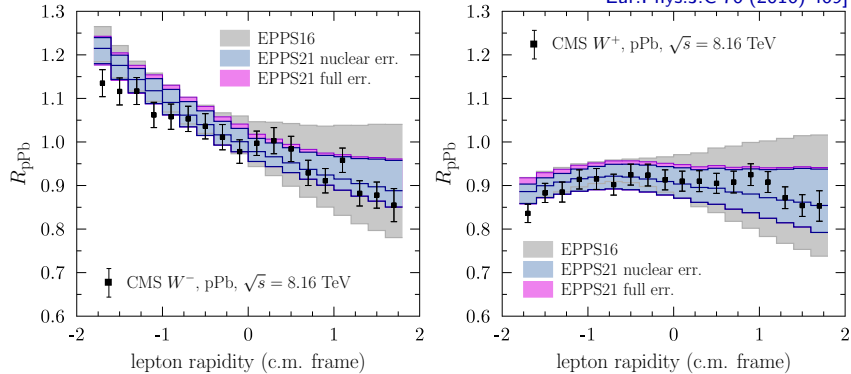
Fully consistent with the dijets and D⁰s

- Important check on the nPDF universality & factorization

These data do not appear to give additional flavour-separation constraints on top of those we had already in EPPS16

- Looking forward to increased precision at LHC Run 3

data from: [CMS Collaboration, Phys.Lett.B 800 (2020) 135048, Eur.Phys.J.C 76 (2016) 469]



Excellent fit!

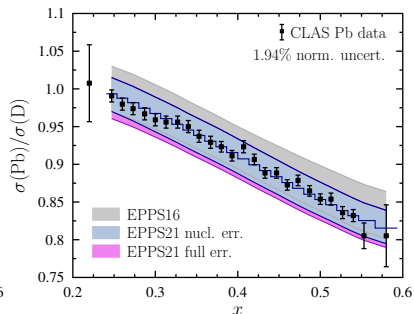
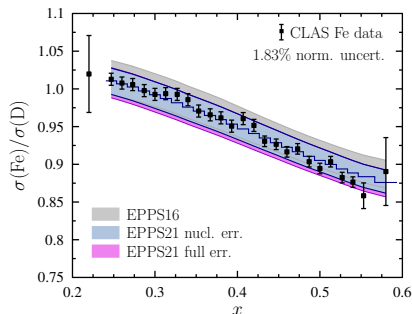
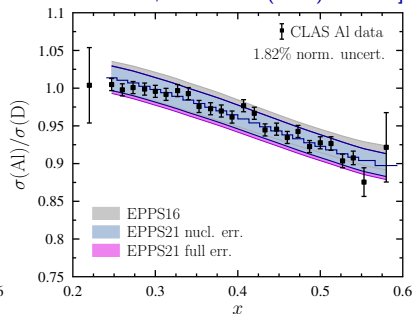
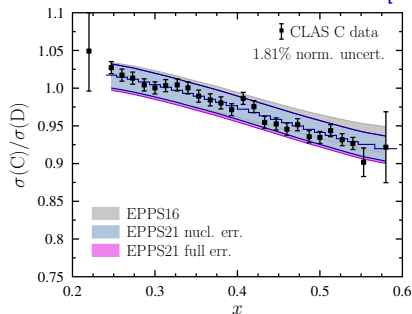
Results in line with
the reweighting study

[Paukkunen & Zurita,
Eur.Phys.J.C 80 (2020) 381]

We take into account
the leading target-mass
corrections

No sign of isospin-dependence
in the bound-proton
nuclear modifications $R_i^{p/A}$

data from: [CLAS Collaboration, Nature 566 (2019) 354-358]

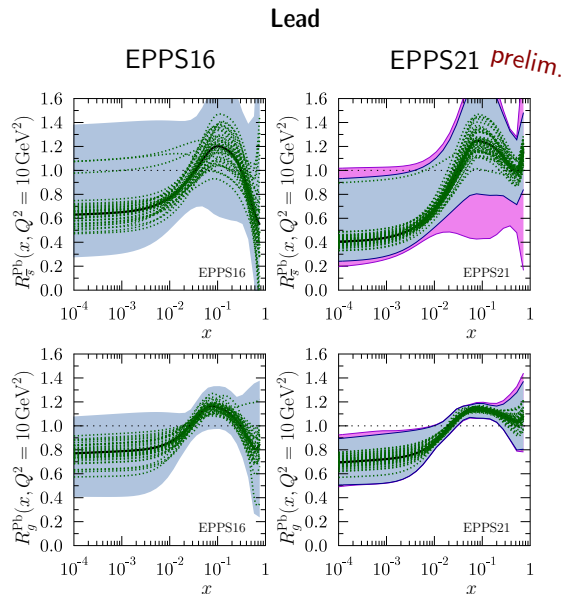


Flavour separation (esp. strangeness) remains a difficult beast to tame

- Not enough data to put stringent constraints on a flavour by flavour basis
- Some sensitivity to proton-PDF uncertainties

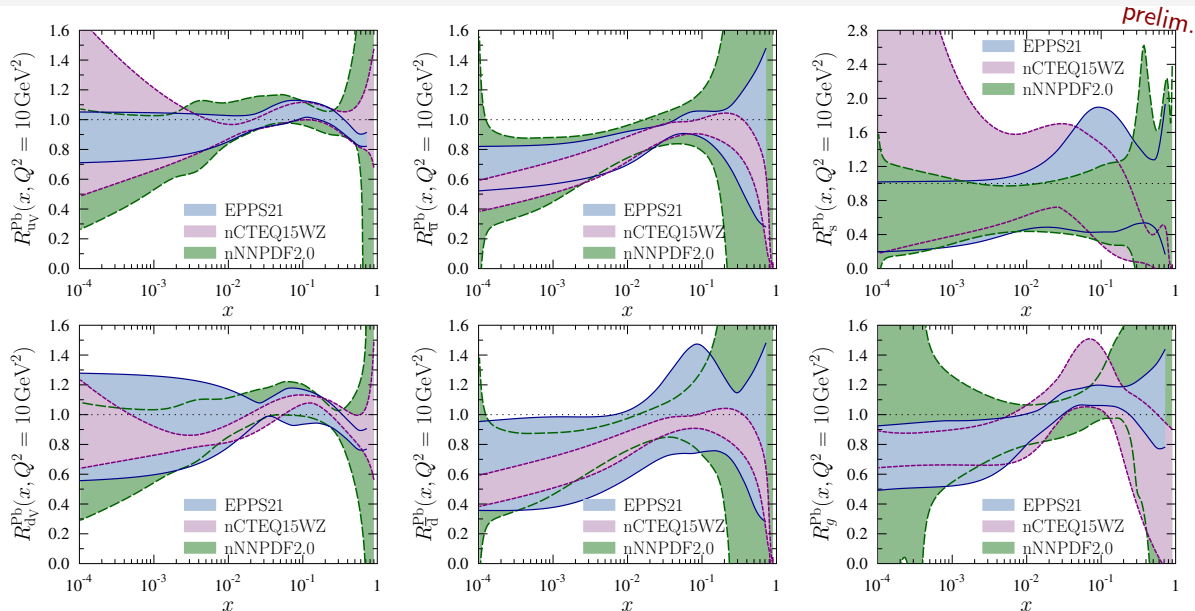
Significant reduction in the gluon uncertainties!

- Driven by dijet and D^0 data, but consistent with Ws
- Strong evidence for mid- x antishadowing and small- x shadowing



Comparison to nNNPDF2.0, nCTEQ15WZ preliminary results,

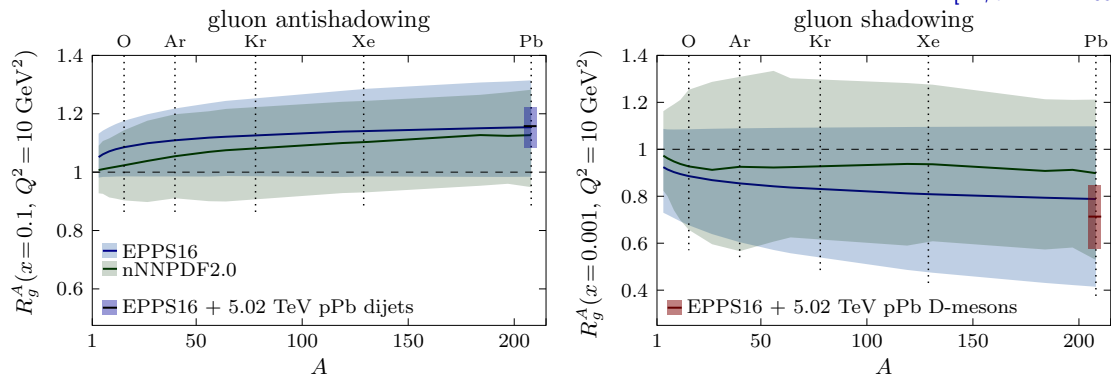
Ref: [Eskola, PP, Paukkunen & Salgado, arXiv:2106.13661]



- All three consistent within uncertainties, but significant differences in the uncertainty estimates
- Best constrained gluons in the EPPS21 *prelim.* fit from pPb dijets and D-mesons!

A -dependence of gluon modifications

[PP, arXiv:2111.05368]



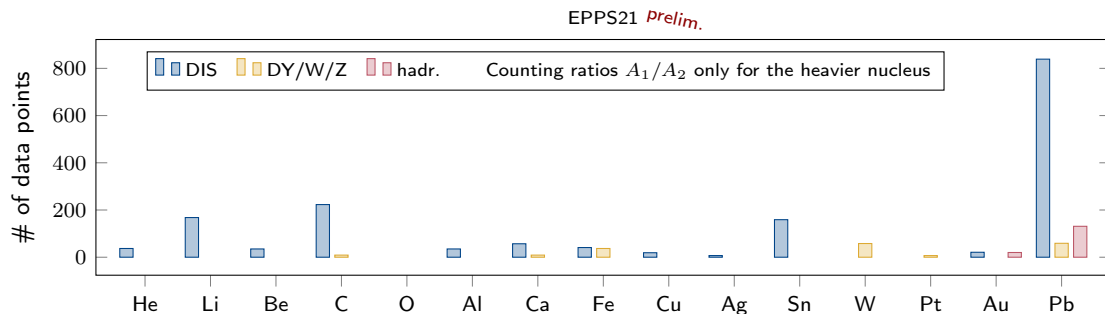
Direct gluon constraints available only for heavy nuclei (most constraining: pPb dijets & D-mesons)

- Gluons and small- x quarks poorly constrained for lighter nuclei
- Significant parametrization dependence

How confidently can we interpolate the light-nuclei gluons from measurements at large A ?

- SMOG@LHCb and RHIC (pA) can help for the large x
- Need for lighter-ion LHC pA runs and EIC!

Data availability w.r.t. A



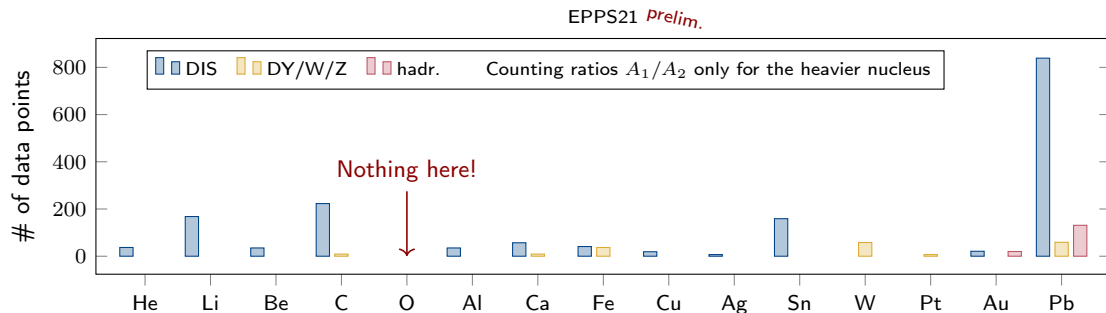
~ 50% of the data points are for Pb!

- 😊 Good coverage of DIS measurements for different A (but only fixed target!)
- 😞 DY data more scarce, but OK A coverage
- 😞 Hadronic observables available only for heavy nuclei!

Light-ion runs at LHC could:

- Complement other light-nuclei DY data with W and Z production (strangeness!)
- Give first direct constraints (e.g. dijets, D-mesons) on light-nuclei gluon distributions!

Data availability w.r.t. A



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Dijet production in pO at 9.9 TeV

Similar setup as in the CMS 5.02 TeV pPb measurement

Total integrated pO cross section of 81 μb

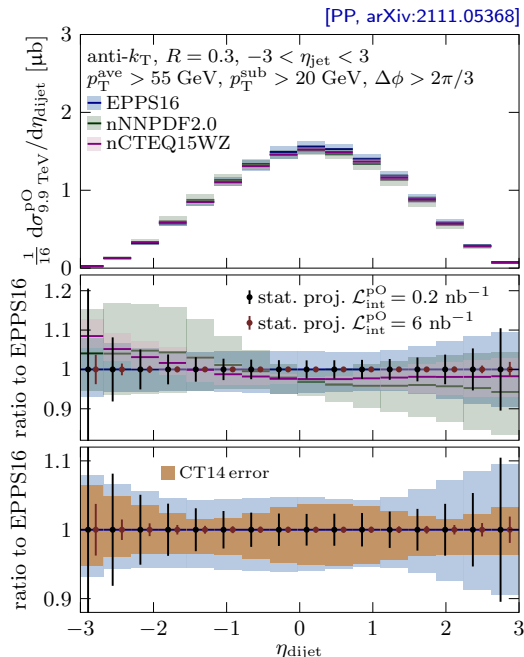
- Compare with $\sim 330 \mu\text{b}$ in pPb at 5.02 TeV
- Sufficient to give reasonable statistics even at relatively low luminosities
 - 16000 events at 0.2 nb^{-1}
 - 486000 events at 6 nb^{-1}

Problem: absolute cross sections very sensitive to the used free-proton PDFs

- Difficult to disentangle nuclear modifications from the free-proton d.o.f.s

Problem: We do not expect a pp reference at 9.9 TeV

- Could we use a mixed energy ratio $\text{pO}(9.9 \text{ TeV})/\text{pp}(8.8 \text{ TeV})$?



N.B. not corrected for NP effects

Dijet $R_{pO}^{\text{norm.}}$ in pO at 9.9 TeV

Problem: We do not expect a pp reference at 9.9 TeV

- Could we use a mixed energy ratio $pO(9.9 \text{ TeV})/pp(8.8 \text{ TeV})$? Yes!

Excellent cancellation of free-proton PDFs

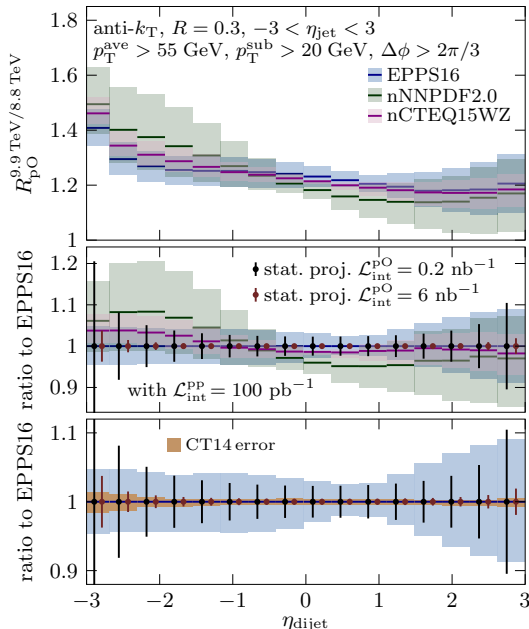
- Direct access to nuclear modifications

Luminosity (and hadronization) uncertainties can be made to cancel with self-normalization, but this would cancel also part of the nPDF effects

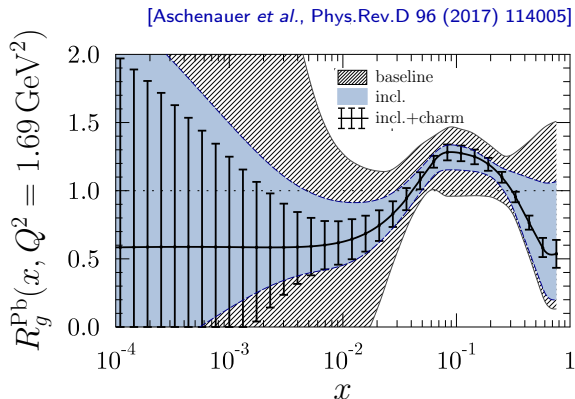
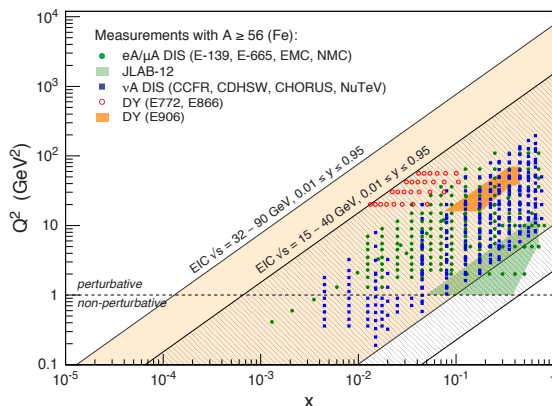
Already few nb^{-1} can be expected to be enough to put new constraints on nPDFs (if we have sufficient statistics for the pp reference)

- Can resolve different nPDF parametrisations!

[PP, arXiv:2111.05368]



Gluon constraints from EIC



EIC will significantly widen the kinematic range of DIS constraints for nPDFs

- Comparing with LHC measurements will put collinear factorization with nuclei to a stringent test

With the F_L extraction capability, EIC provides a clean probe to study small- x gluons

- Good constraining power to well down to 10^{-2} in a high-energy scenario

Charm-tagged cross-section measurement can vastly reduce high- x gluon uncertainty

see also: [Kelsey *et al.*, Phys.Rev.D 104 (2021) 054002]

Limits of applicability – large and small x

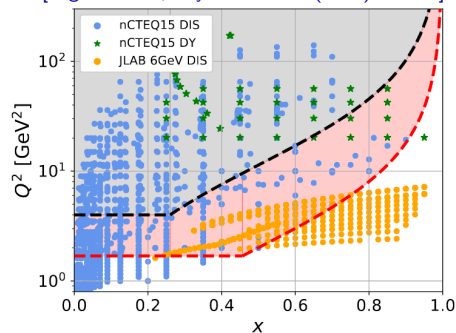
Large x subject to target-mass and higher-twist corrections

- Do these have sizable effect? (Yes)
- Can we still get a good fit with traditional nPDFs? (Yes)
- Any need for isospin-dependent modifications? (No)

[Paukkunen & Zurita, Eur.Phys.J.C 80 (2020) 381]

[Segarra *et al.*, Phys.Rev.D 103 (2021) 114015]

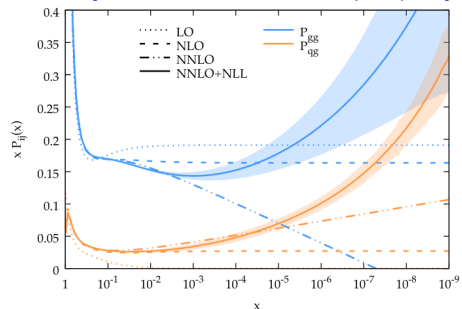
[Segarra *et al.*, Phys.Rev.D 103 (2021) 114015]



Expect gluon density to saturate at small x

- When does the simple DGLAP picture break down?
- What experimental signatures do we need?

[Bonvini & Marzani, JHEP 06 (2018) 145]



Small- x corrections already in the linear phase (BFKL)

- Do these become important before saturation kicks in?
- Need resummation and/or higher orders

→ Many opportunities for the EIC!

Higher orders – the pursue for NNLO

[Walt, Helenius & Vogelsang, Phys.Rev.D 100 (2019) 096015]

Several NNLO analyses appeared over the past years

- KA15 [PRD 93 (2016) 014026] (NC DIS, DY)
- nNNPDF1.0 [EPJ C79 (2019) 471] (NC DIS)
- TuJu19 [PRD 100 (2019) 096015] (NC DIS, CC ν -DIS)
- KSASG20 [PRD 104 (2021) 034010] (NC DIS, CC ν -DIS)

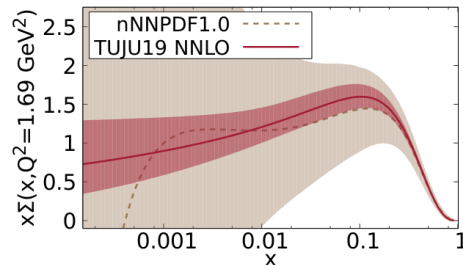
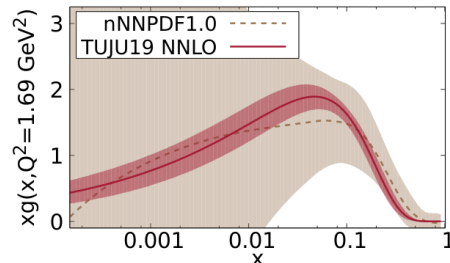
Limited currently to fixed-target data

- No direct gluon constraints
- Large uncertainties / parametrization dependence

Future prospects:

- Public codes available for DY/W/Z at NNLO
- For hadronic observables NNLO calculations exist, but no public codes yet available

NNLO the standard for EIC?



Summary

Next generation nuclear PDFs will include a large set of data from the LHC pPb collisions

- New constraints on gluon modifications in lead → strong evidence for (anti)shadowing!
- Flavour separation uncertainties still remain large and contain some free-proton PDF uncertainty
- A new EPPS nPDF fit on its way...

A -dependence of gluon PDF poorly known

- Significant parametrization dependence in global analyses
- Already few nb^{-1} in pO could help us better understand gluon modifications in light nuclei

EIC will put collinear factorization with nuclei to a stringent test

- Inclusive and charm-tagged measurements able to put new constraints on gluon nPDFs
- Availability of wide spectrum of nuclear beams highly important

Backup

Fit results – valence

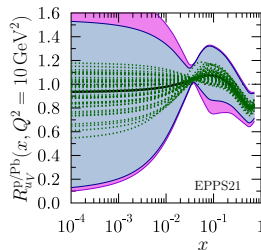
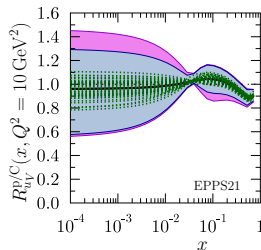
preliminary results,
Ref: [Eskola, PP, Paukkunen & Salgado, arXiv:2106.13661]

Bound-proton modifications *Prelim.*

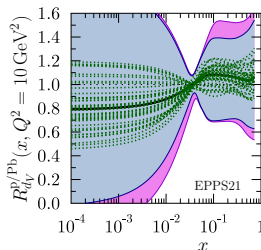
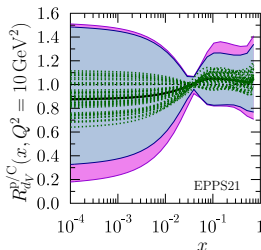
Carbon

Lead

u_V



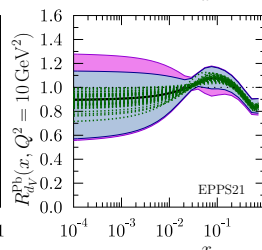
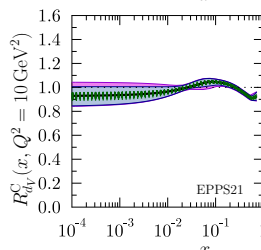
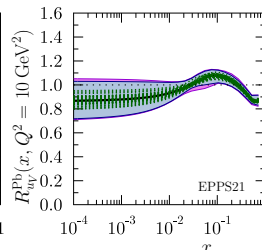
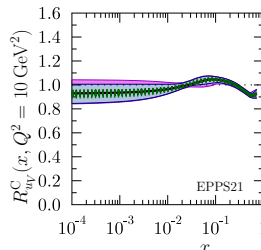
d_V



Full-nucleus modifications *Prelim.*

Carbon

Lead



$$R_i^{p/A} = \frac{f_i^{p/A}}{f_i^p}$$

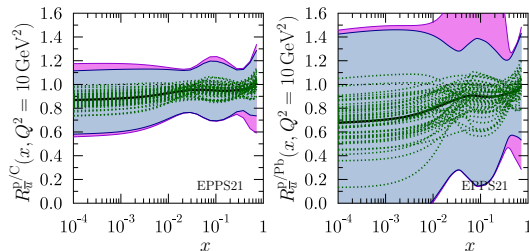
$$R_i^A = \frac{Z f_i^{p/A} + N f_i^{n/A}}{Z f_i^p + N f_i^n}$$

Bound-proton modifications *Prelim.*

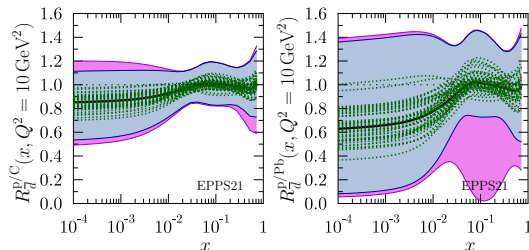
Carbon

Lead

\bar{u}



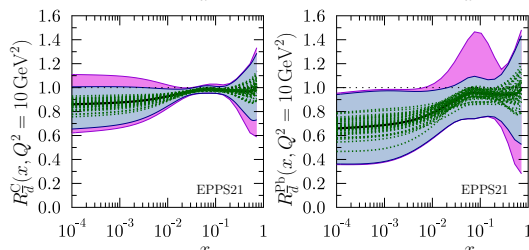
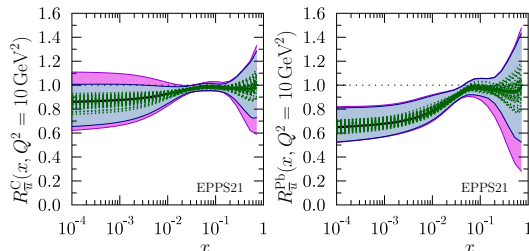
\bar{d}



Full-nucleus modifications *Prelim.*

Carbon

Lead



$$R_i^{p/A} = \frac{f_i^{p/A}}{f_i^p}$$

$$R_i^A = \frac{Z f_i^{p/A} + N f_i^{n/A}}{Z f_i^p + N f_i^n}$$

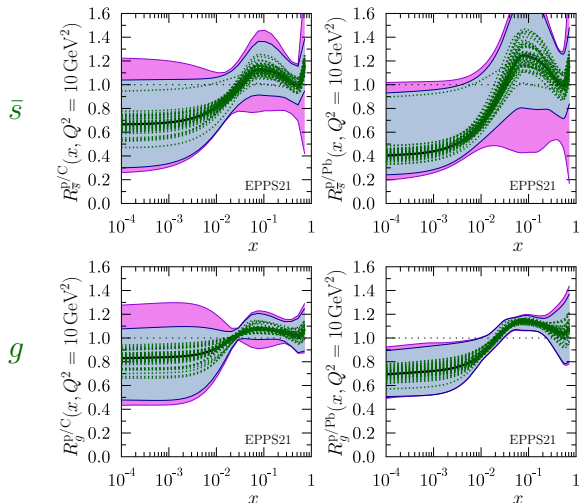
Fit results – strange and glue

preliminary results,
Ref: [Eskola, PP, Paukkunen & Salgado, arXiv:2106.13661]

Bound-proton modifications *Prelim.*

Carbon

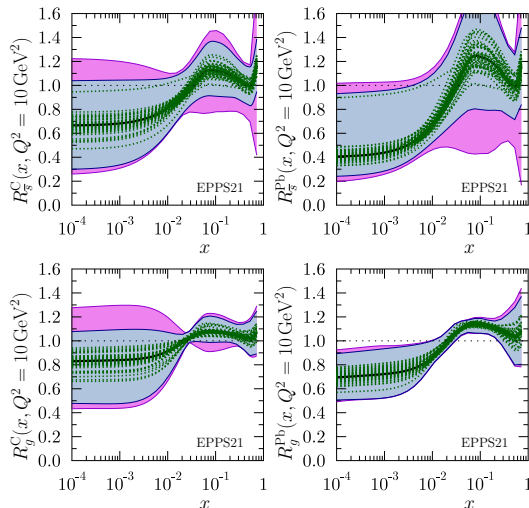
Lead



Full-nucleus modifications *Prelim.*

Carbon

Lead



$$R_i^{p/A} = \frac{f_i^{p/A}}{f_i^p}$$

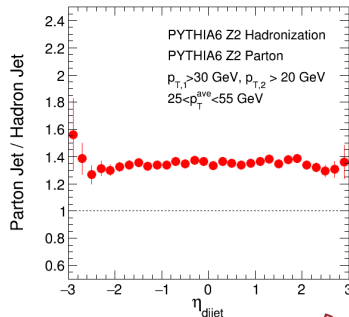
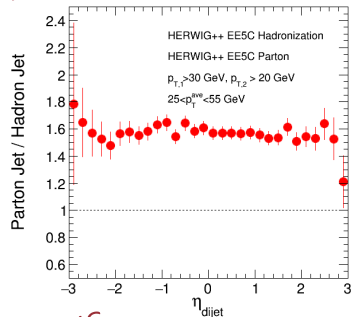
$$R_i^A = \frac{Z f_i^{p/A} + N f_i^{n/A}}{Z f_i^p + N f_i^n}$$

HERWIG

Cross-section ratios

PYTHIA

*Hadronization
uncertainty*



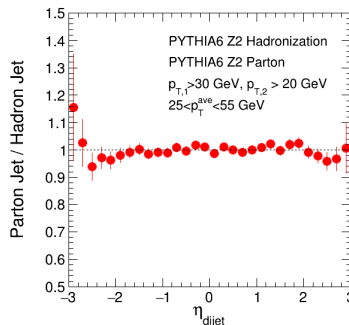
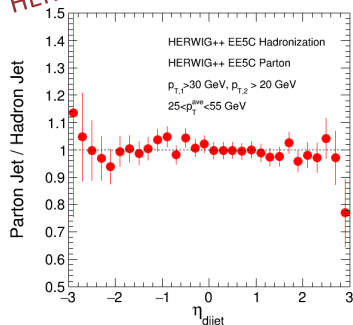
Parton jets have higher cross section for $R = 0.3$ jets with same kinematic selections compared to hadron jets

Parton jets are harder fragmenting

HERWIG

Area normalized ratios

PYTHIA

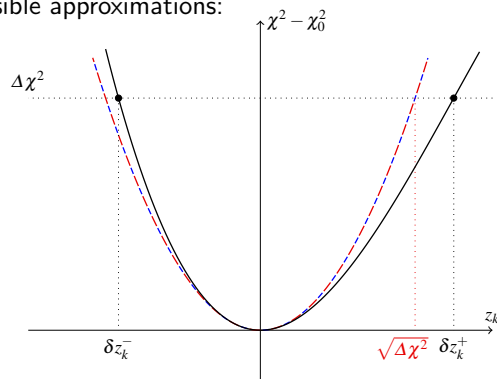


After self normalization effect of hadronization is negligible

The Hessian reweighting is a method to study the impact of a new set of data on the PDFs without performing a full global fit

$$\chi_{\text{new}}^2(\mathbf{z}) = \chi_{\text{old}}^2(\mathbf{z}) + \sum_{ij} (y_i(\mathbf{z}) - y_i^{\text{data}}) C_{ij}^{-1} (y_j(\mathbf{z}) - y_j^{\text{data}})$$

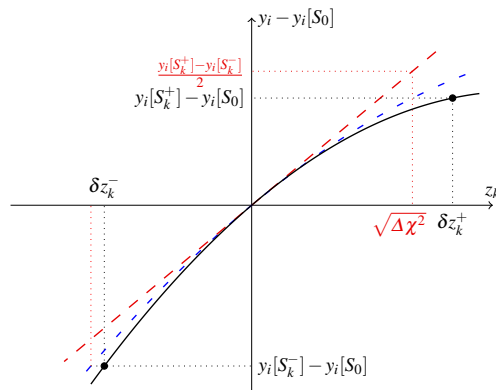
Possible approximations:



quadratic-linear: $\chi_{\text{old}}^2 \approx \chi_0^2 + \sum_k z_k^2$,

quadratic-quadratic: $\chi_{\text{old}}^2 \approx \chi_0^2 + \sum_k z_k^2$,

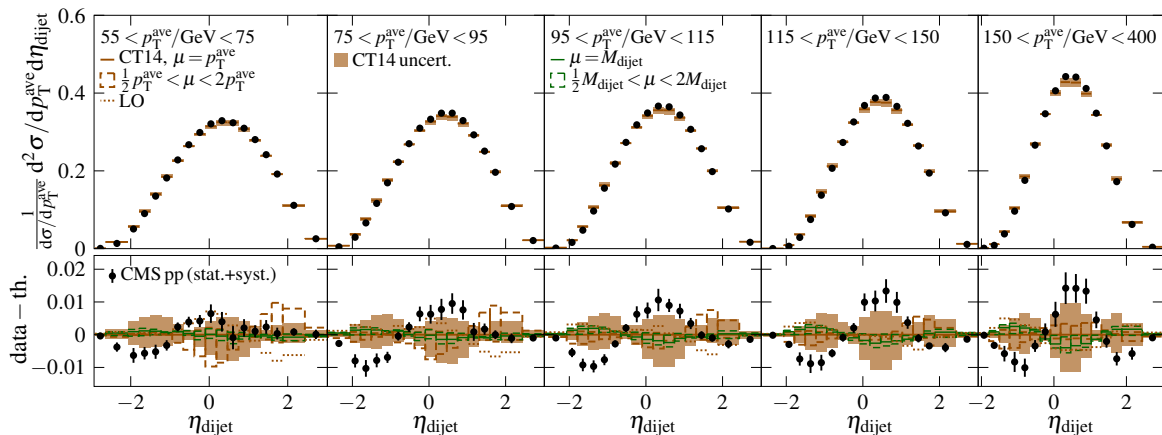
cubic-quadratic: $\chi_{\text{old}}^2 \approx \chi_0^2 + \sum_k (a_k z_k^2 + b_k z_k^3)$,



$y_i \approx y_i[S_0] + \sum_k d_{ik} z_k$

$y_i \approx y_i[S_0] + \sum_k (d_{ik} z_k + e_{ik} z_k^2)$

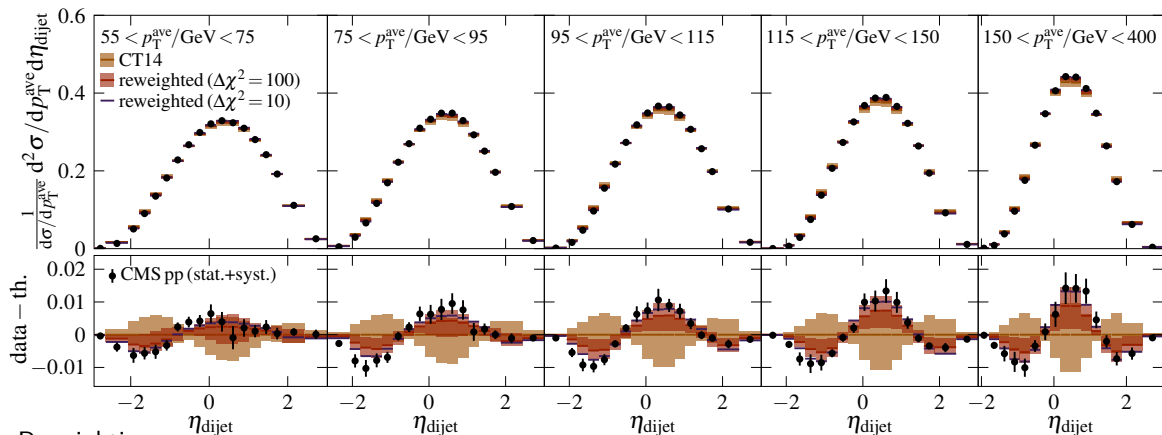
$y_i \approx y_i[S_0] + \sum_k (d_{ik} z_k + e_{ik} z_k^2)$



- Predicted NLO distributions somewhat wider than the measured spectra
- High- p_T^{ave} midrapidity robust against scale variations and LO-to-NLO effects
 - can expect NNLO corrections to be small in this region
 - observed discrepancy seems to be a PDF related issue
- Refitting might be needed to improve agreement with data
 - study the impact with the reweighting method

CMS dijets at pp – CT14 reweighted

[Eskola, PP & Paukkunen, Eur.Phys.J.C 79 (2019) 511]

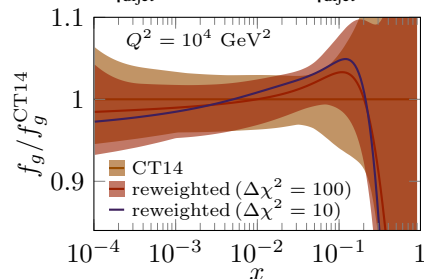


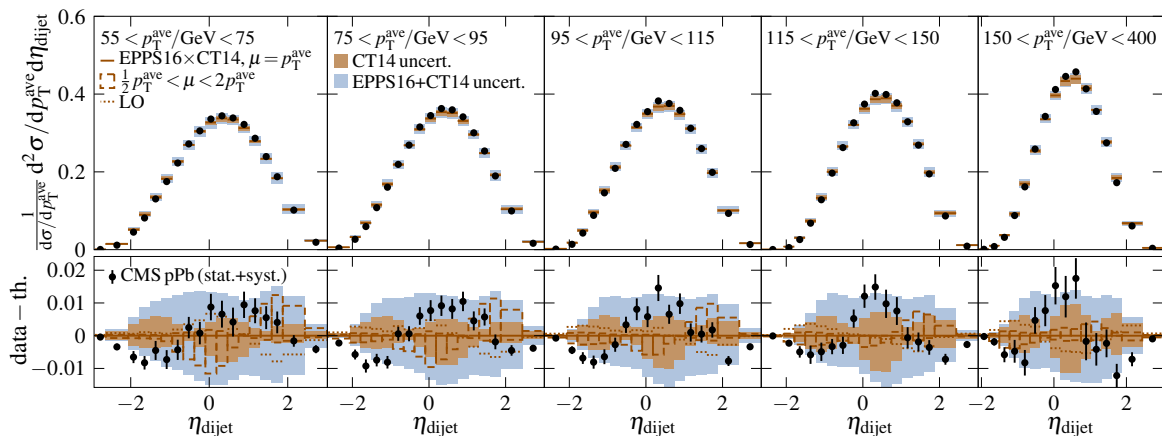
Rewighting:

- improves midrapidity description
- is not able to fully reproduce data at large rapidities even when applied with additional weight ($\Delta\chi^2 = 10$) (high- x parametrization issue? NNLO? data systematics?)

Significant gluon modifications needed especially at large x

- also valence quarks get modified

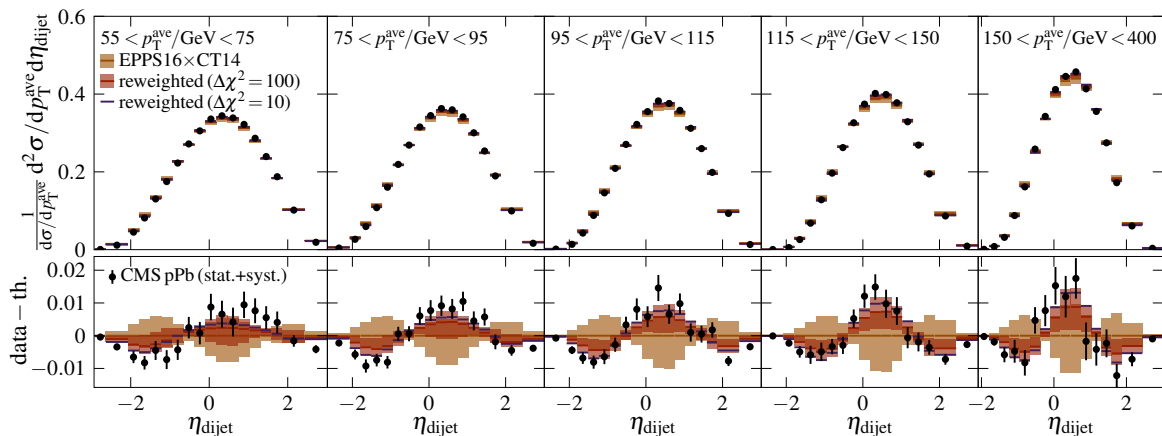




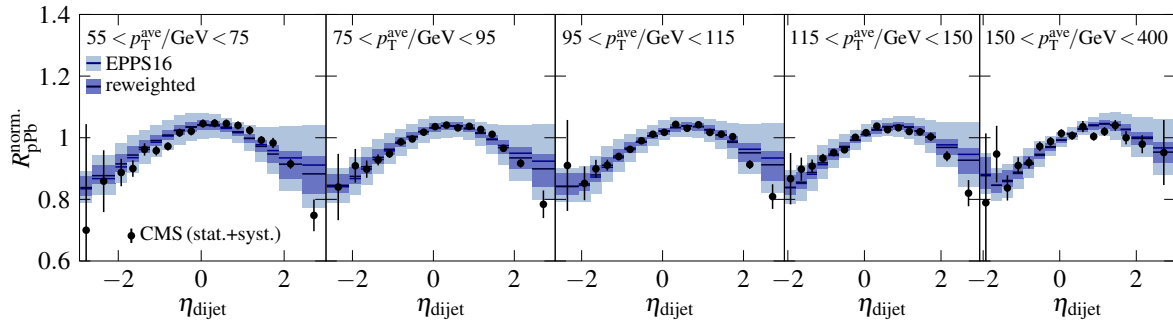
- pPb data deviates from NLO calculations *almost the same way* as the pp data
 - had we not seen the same deviations in pp, we might have interpreted this as a fault in our nuclear PDFs
- Compared to pp case we have additional suppression in data compared to theory at forward rapidities
 - implication of deeper gluon shadowing

CMS dijets at **pPb** after CT14 reweighting

[Eskola, PP & Paukkunen, Eur.Phys.J.C 79 (2019) 511]



- Modifications needed in CT14 to describe pp data have large impact on pPb predictions
 - it is imperative to understand the pp baseline before making far-reaching conclusions from pPb data
 - Using these data directly in nuclear PDF analysis with CT14 proton PDFs would lead to
 - ▶ overestimating nuclear effects
 - ▶ large scale-choice bias
- Consider nuclear modification factor instead

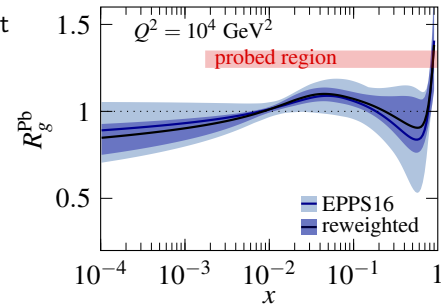


A Hessian PDF reweighting study shows that these data can put stringent constraints on the gluon modifications

- Drastic reduction in EPPS16 gluon uncertainties
- Support for mid- x antishadowing and small- x shadowing
- Probes the onset of shadowing down to $x > 10^{-3}$

Remaining questions:

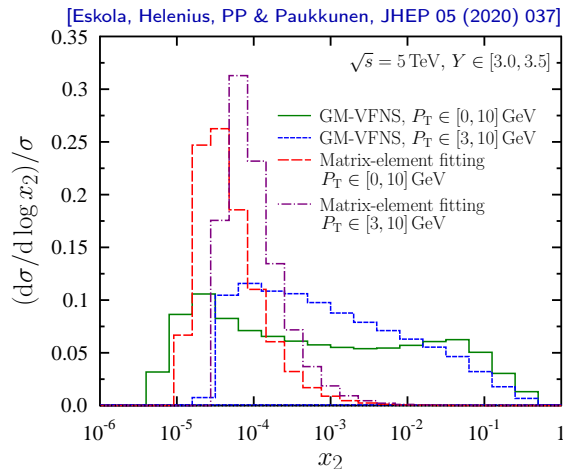
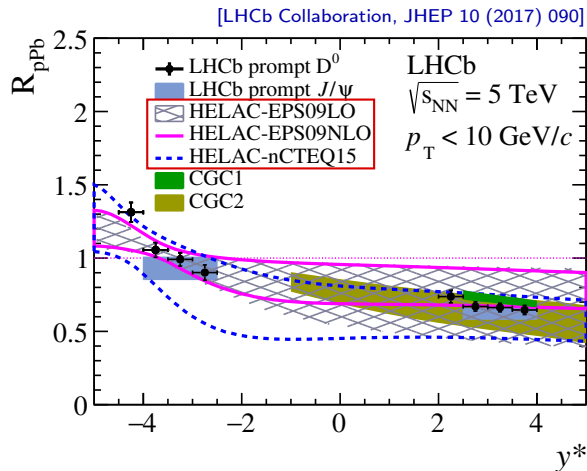
- Is there EMC suppression for gluons?
- What happens at $x < 10^{-3}$?



$$R_i^A(x, Q^2) = \frac{f_i^{\text{p/A}}(x, Q^2)}{f_i^{\text{p}}(x, Q^2)}$$

bound-proton PDF free-proton PDF

D-mesons at 5.02 TeV – differences in theoretical descriptions



Data can probe nPDFs down to $x \sim 10^{-5}$, but x sensitivity differs between theoretical approaches:

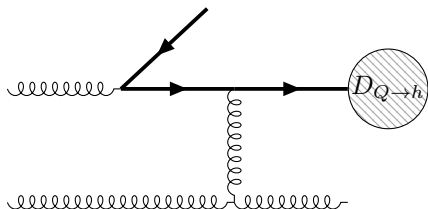
- The HELAC framework [Lansberg & Shao, EPJ C77 (2017) 1] uses a matrix-element fitting method with $2 \rightarrow 2$ kinematics producing a narrow distribution in x (can be used also for quarkonia)
- The SACOT- m_T scheme [Helenius & Paukkunen, JHEP 1805 (2018) 196] of GM-VFNS NLO pQCD gives a much wider x -distribution due to taking into account the gluon-to-HQ fragmentation

Heavy-flavour production mass schemes

FFNS

In *fixed flavour number scheme*, valid at small p_T , heavy quarks are produced only at the matrix element level

Contains $\log(p_T/m)$ and m/p_T terms

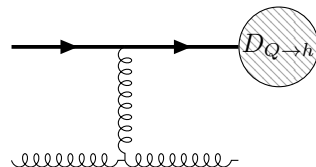


ZM-VFNS

In *zero-mass variable flavour number scheme*, valid at large p_T , heavy quarks are treated as massless particles produced also in ISR/FSR

Resums $\log(p_T/m)$ but ignores m/p_T terms

– subtraction term +



GM-VFNS

A *general-mass variable flavour number scheme* combines the two by supplementing subtraction terms to prevent double counting of the resummed splittings, valid at all p_T

Resums $\log(p_T/m)$ and includes m/p_T terms in the FFNS matrix elements

Important: includes also **gluon-to-HF fragmentation** – large contribution to the cross section!

D-mesons at 5.02 TeV – nPDFs reweighted

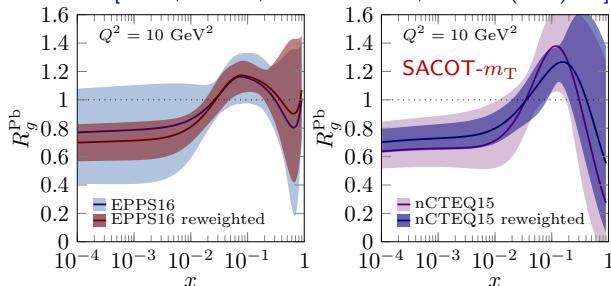
R_{pPb} mostly insensitive to the differences

- Reweighting with the two methods give compatible results for R_g^{Pb}
see the refs. for comparison with POWHEG+PYTHIA, FONLL
- Large reduction in small- x uncertainties, probed down to $x \sim 10^{-5}$
- EPPS16 and nCTEQ15 brought to a closer mutual agreement

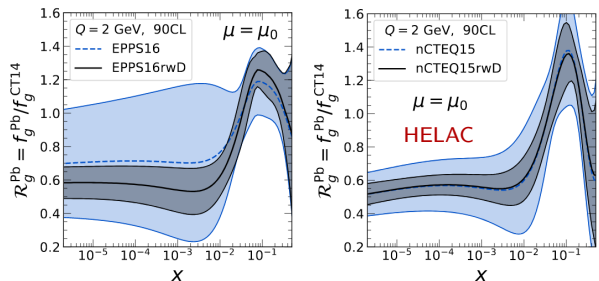
Striking similarity with the results with dijets

- Supports the validity of collinear factorization in pPb and the universality of nPDFs
 - further confirmation possible from forward photons, low-mass DY & W/Z-bosons

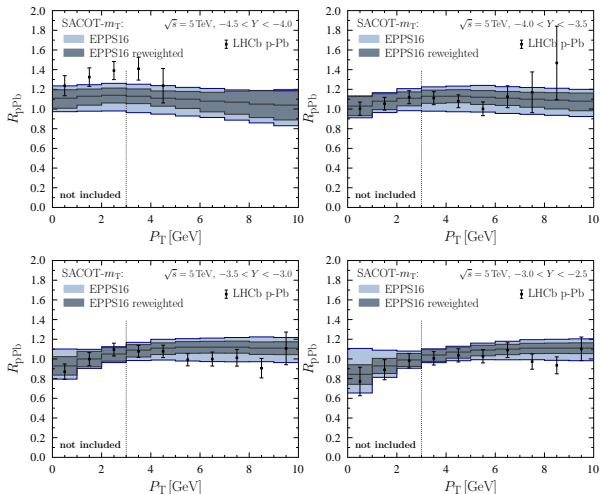
[Eskola, Helenius, PP & Paukkunen, JHEP 05 (2020) 037]



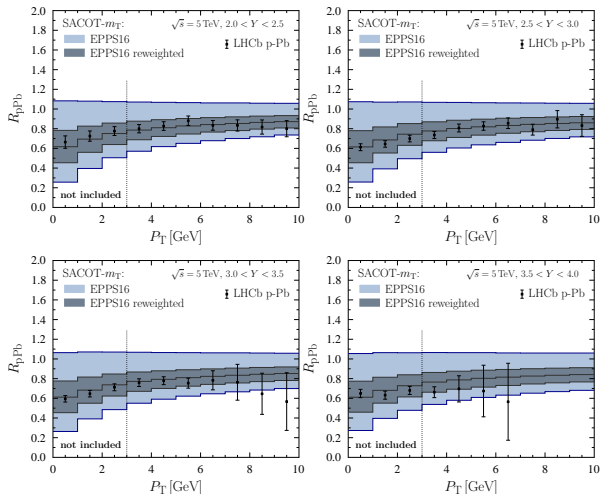
[Kusina, Lansberg, Schienbein & Shao, PRL 121 (2018) 052004, fig. from arXiv:2012.11462]



Backward



Forward

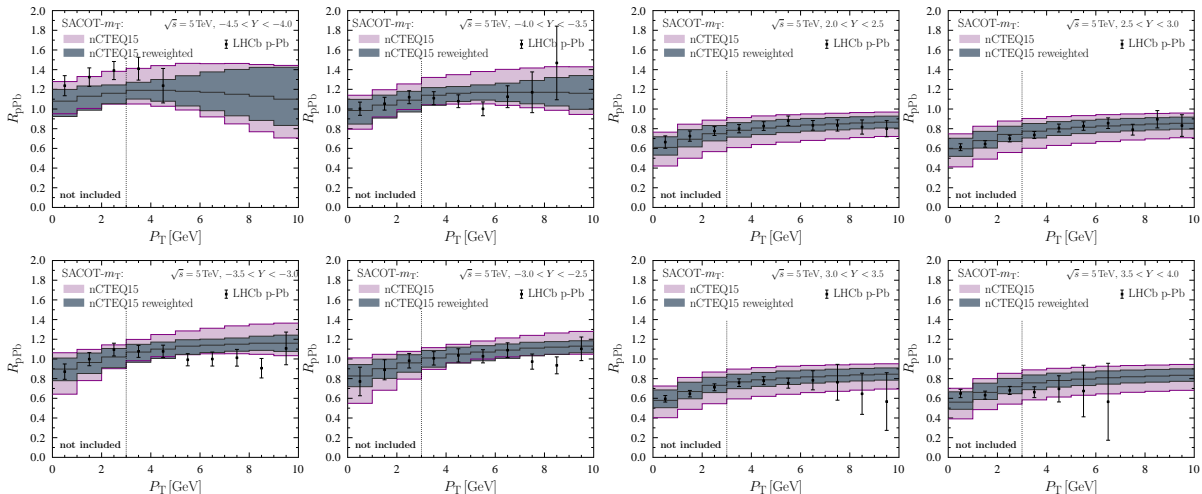


- Data well reproduced with the reweighted results
- Significant reduction in EPPS16 uncertainties especially in forward bins
- Good agreement with data below cut – no physics beyond collinear factorization needed

nCTEQ15 reweighted LHCb D-meson R_{pPb} [Eskola, Helenius, PP & Paukkunen, JHEP 05 (2020) 037]

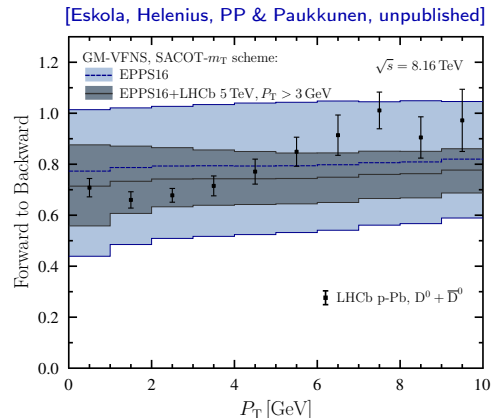
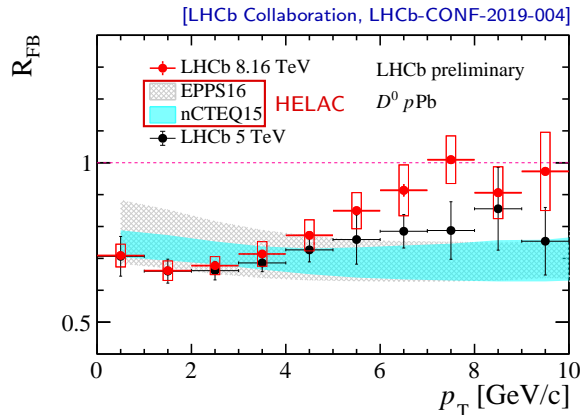
Backward

Forward



- Uncertainties smaller to begin with in the forward direction (less flexible small- x parametrization) while larger in backward – almost identical results
- Data well reproduced

D-mesons at 8.16 TeV – do we have tension?



QM2019 LHCb summary talk:

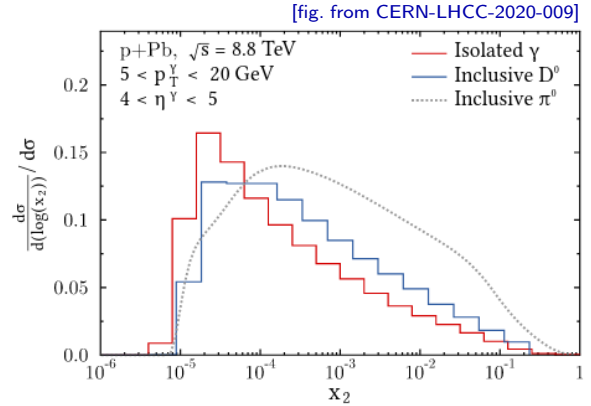
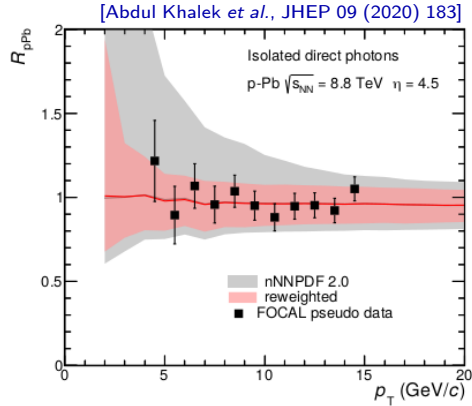
“Tension between data and nPDFs predictions. Additional effects required.”

→ Theoretical description matters, HELAC predicts much smaller nPDF uncertainties for R_{FB} than SACOT- m_T !

The slope of the 8.16 TeV data still differs from that in nPDF predictions and in 5.02 TeV data

→ How can we explain the difference?

Future prospects: Forward photons with FoCal



Isolated photons at forward rapidities are a good probe of the nuclear small- x gluons

- Isolation cut reduces the fragmentation component
 - enhanced small- x sensitivity [Helenius *et al.*, JHEP 09 (2014) 138]
- Test for the possible onset of non-linear QCD effects
- Complementary to the forward D^0 s and DY [cf. CERN Yellow Rep.Monogr. 7 (2019), pp. 1312-1313]

u and d valence quark modifications (in lead)

Most nuclei are close to isoscalar

→ Nearly equal amount of u and d quarks

For example, we can write

$$f_{u_V}^A = R_{u_V+d_V}^A \left(1 - \frac{A-2Z}{A} \mathcal{A}_{u_V-d_V}^A \right) \frac{A}{2} (f_{u_V}^p + f_{d_V}^p)$$

$$f_{d_V}^A = R_{u_V+d_V}^A \left(1 + \frac{A-2Z}{A} \mathcal{A}_{u_V-d_V}^A \right) \frac{A}{2} (f_{u_V}^p + f_{d_V}^p)$$

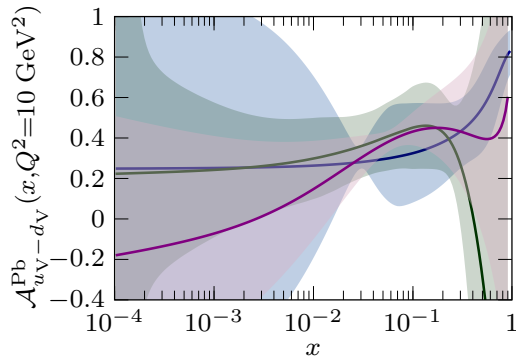
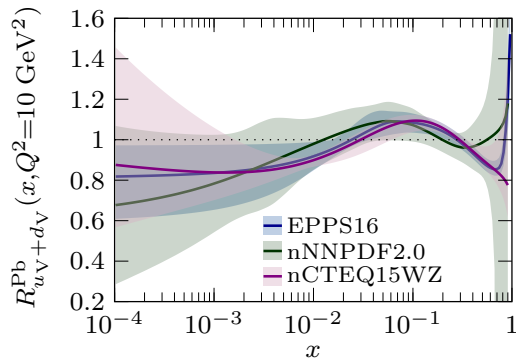
where

$$R_{u_V+d_V}^A = \frac{f_{u_V}^{p/A} + f_{d_V}^{p/A}}{f_{u_V}^p + f_{d_V}^p} \quad \mathcal{A}_{u_V-d_V}^A = \frac{f_{u_V}^{p/A} - f_{d_V}^{p/A}}{f_{u_V}^{p/A} + f_{d_V}^{p/A}}$$

and neutron excess $\frac{A-2Z}{A} \approx 0.2$ for Pb

→ Need high-precision data on non-isoscalar nuclei to constrain the asymmetry

Important for studying the physical origin of the EMC effect



u and \bar{d} sea quark modifications (in lead)

Most nuclei are close to isoscalar

→ Nearly equal amount of \bar{u} and \bar{d} quarks

Here

$$f_{\bar{u}}^A = R_{\bar{u}+\bar{d}}^A \left(1 - \frac{A-2Z}{A} \mathcal{A}_{\bar{u}-\bar{d}}^A \right) \frac{A}{2} (f_{\bar{u}}^p + f_{\bar{d}}^p)$$

$$f_{\bar{d}}^A = R_{\bar{u}+\bar{d}}^A \left(1 + \frac{A-2Z}{A} \mathcal{A}_{\bar{u}-\bar{d}}^A \right) \frac{A}{2} (f_{\bar{u}}^p + f_{\bar{d}}^p)$$

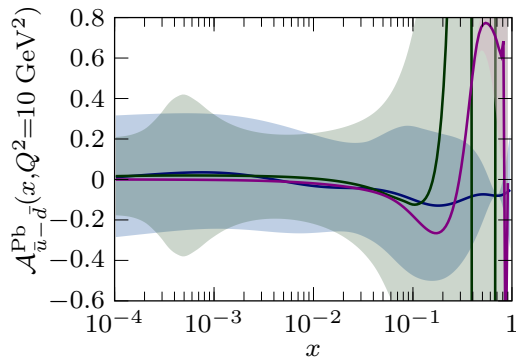
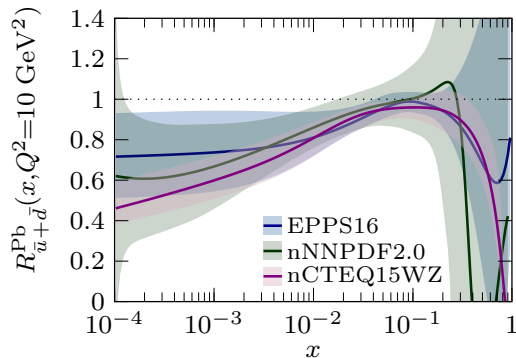
with

$$R_{\bar{u}+\bar{d}}^A = \frac{f_{\bar{u}}^{p/A} + f_{\bar{d}}^{p/A}}{f_{\bar{u}}^p + f_{\bar{d}}^p} \quad \mathcal{A}_{\bar{u}-\bar{d}}^A = \frac{f_{\bar{u}}^{p/A} - f_{\bar{d}}^{p/A}}{f_{\bar{u}}^{p/A} + f_{\bar{d}}^{p/A}}$$

Flavour asymmetry only a small correction

nNNPDF2.0 does not use fixed-target DY data

→ less constraints for valence/sea separation compared to EPPS16 & nCTEQ15WZ



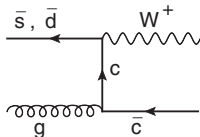
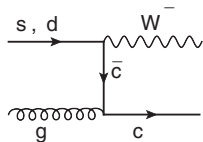
Gluon and strange modifications (in lead)

The gluon and strange modifications are poorly constrained in the current nPDF releases

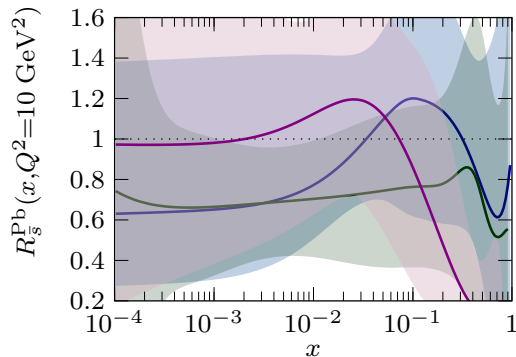
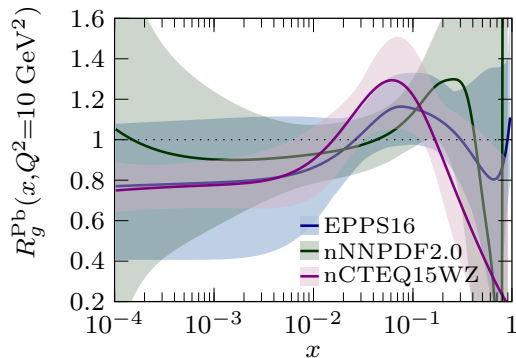
- Better gluon constraints are available from LHC pPb dijets and D-mesons, but these need to be included in the global analyses (in progress)

The existing LHC pPb W/Z data did not give strong constraints for the strangeness

- Additional data needed
- W+charm measured in pp, doable in pPb?



$$R_i^A(x, Q^2) = \underbrace{f_i^{P/A}}_{\text{bound-proton PDF}}(x, Q^2) / \underbrace{f_i^P}_{\text{free-proton PDF}}(x, Q^2)$$



Average u and d quark modifications (in oxygen)

The average u and d valence and sea modifications

$$R_{u_V+d_V}^A = \frac{f_{u_V}^{p/A} + f_{d_V}^{p/A}}{f_{u_V}^p + f_{d_V}^p} \quad R_{\bar{u}+\bar{d}}^A = \frac{f_{\bar{u}}^{p/A} + f_{\bar{d}}^{p/A}}{f_{\bar{u}}^p + f_{\bar{d}}^p}$$

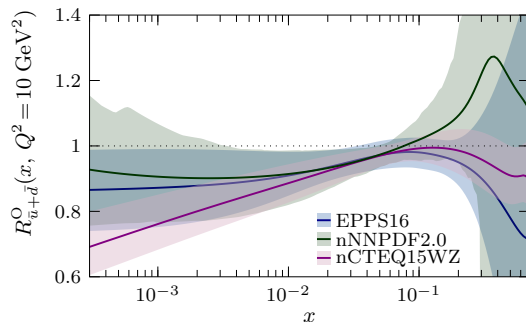
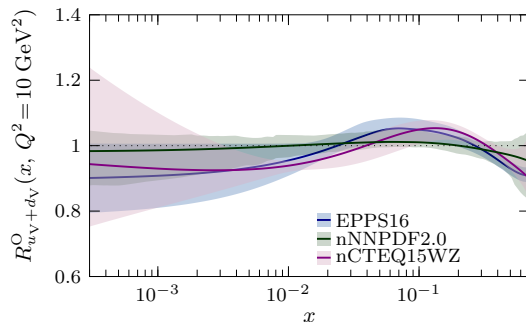
are under control (from interpolation)

Oxygen fully isoscalar

- No contribution from flavour asymmetry!
- From nPDF point of view, oxygen is “simpler” than lead

nNNPDF2.0 differs (again) from EPPS16 and nCTEQ15WZ due to not having fixed-target DY data

- Data from E772 indicate that there should be antishadowing for valence, but not for sea quarks

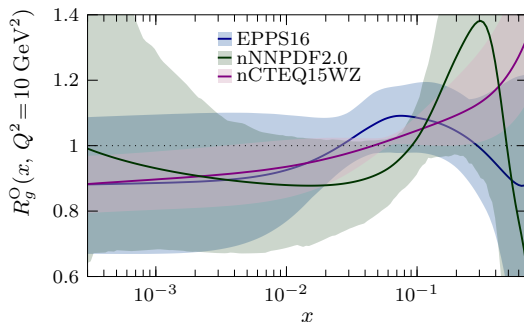


Gluon and strange modifications (in oxygen)

$$R_i^A(x, Q^2) = \underbrace{f_i^{P/A}}_{\text{bound-proton PDF}}(x, Q^2) / \underbrace{f_i^P}_{\text{free-proton PDF}}(x, Q^2)$$

No agreement for the shape of gluon modifications!

- ! No direct data constraints available
- Can cause significant uncertainties e.g. for jet R_{OO}
- We could expect major improvement from a LHC pO run



Large uncertainties also for the strange quark

- nNNPDF2.0 has smaller uncertainties here likely due to including NuTeV νFe CC DIS data
- Since u/d flavour asymmetry does not contribute (isoscality), measuring W/Z bosons in pO/OO could provide unique constraints for strangeness nuclear modifications

